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INFLUENCE OF STORM-RELATED SEDIMENT STORAGE ON THE SEDIMENT DELIVERY FROM TRIBUTARY CATCHMENTS IN THE UPPER WAIPAOA RIVER, NEW ZEALAND

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ABSTRACT

Although much is known about overall sediment delivery ratios for catchments as components of sediment production and sediment yield, little is known about the component of temporary sediment storage. Sediment delivery ratios focused on the influence of storm-related sediment storage are measured at Matakonekone and Oil Springs tributaries of the Waipaoa River basin, east coast of New Zealand. The terrace deposits of both tributaries show abundant evidence of storm-related sedimentation, especially sediment delivered from Cyclone Bola, a 50 year return rainfall event which occurred in 1988. The sediment delivery ratio is calculated by dividing the volume of sediment transported from a tributary to the main stream by the volume of sediment generated at erosion sites in the tributary catchment. Because the sediment delivery volume is unknown, it can be calculated as the difference between sediment generation volume and sediment storage volume in the channel reach of the tributary. The volume of sediment generated from erosion sites in each tributary catchment was calculated from measurements made on aerial photographs dating from 1960 (1:44 000) and 1988 (1:27 000). The volume of sediment stored in the tributary can be calculated from measurements of cross-sections located along the tributary channel, which are accompanied by terrace deposits dated by counting annual growth rings of trees on terrace surfaces.

Sediment delivery ratios are 0·93 for both Matakonekone catchment and Oil Springs catchment. Results indicate that Oil Springs catchment has contributed more than twice the volume of sediment to the Waipaoa River than the Matakonekone catchment ($2{\cdot}75 \times 10^6$ m^3 vs $1{\cdot}22 \times 10^6$ m^3). Although large volumes of sediment are initially deposited during floods, subsequent smaller flows scour away much of these deposits. The sediment scouring rate from storage is $1{\cdot}25 \times 10^4$ m^3 a^{-1} for Matakonekone stream and $0{\cdot}83 \times 10^4$ m^3 a^{-1} for Oil Springs stream. Matakonekone and Oil Springs channels respond to extreme storms by instantaneously aggrading, then gradually excavating the temporarily stored sediment. Results from Matakonekone and Oil Springs streams suggest a mechanism by which event recurrence interval can strongly influence the magnitude of a geomorphic change. Matakonekone stream with its higher stream power is expected to excavate sediment deposits more rapidly and allow more rapid re-establishment of storage capacity.

KEY WORDS: sediment delivery ratio; tributary; sediment storage volume; sediment generation volume; sediment scouring rate

INTRODUCTION

Because tributary catchments differ in the efficiency with which eroded sediment is delivered to a downstream channel, tributary catchments differ also in the extent to which they contribute to the downstream sediment transport regime. Estimates of sediment input from tributary channels are thus required if the behaviour of the main-stream channel is to be predicted. These sediment input rates are expected to be controlled by the sediment delivery processes active in the tributary catchments.

Past research on sediment delivery has attempted to link the rate of erosion within a catchment to the catchment's sediment yield (e.g. Maner, 1958; Roehl, 1962; Wade and Heady, 1978; Williams, 1977; Caine and Swanson, 1989). Erosion rates are generally measured at particular sites, and results are extrapolated to characterize the catchment as a whole using a sediment budget approach. For these studies, sediment yields

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are usually calculated from gauging-station records of sediment loads. Comparison of total sediment input to total sediment output then produces an estimate of the sediment delivery ratio.

The sediment delivery problem can take on a variety of other forms, however, depending on the particular focus of the studies in which sediment delivery is considered. The ratio between erosion on hillslopes and sediment delivered to stream channels has been considered on the scale of entire catchments in efforts to understand the relation between land-use change and soil erosion (e.g. Wischmeier and Smith, 1965; Flacke *et al.*, 1990; Trustrum *et al.*, 1999). In contrast, other studies have focused on explaining channel changes along particular channel reaches, and these have employed sediment delivery ratios calculated for specific parts of a catchment (Schumm and Hadley, 1957; Wolman, 1977; Trimble, 1978).

Comprehensive reviews of sediment delivery studies (e.g. Walling, 1983; Richards, 1993) demonstrate that delivery ratios vary widely between catchments, and that ratios depend to some extent on catchment area, implying the need to consider the role of both hillslope and channel sediment transport processes. Caine and Swanson (1989), in particular, emphasize the need to understand sediment delivery both from hillslopes and within the channel system in small catchments. Meade (1982) and Pickup (1985) proposed dividing catchments into distinct zones of sediment production, transport and deposition to aid in describing sediment budgets.

Although much is thus known about overall sediment delivery ratios for catchments and about components of sediment production and sediment yield, surprisingly little is known about the component of temporary sediment storage. Storage elements have the capacity to buffer the effects of large storms, and they introduce a component of lag into otherwise simple balances between sediment input and output. Response of changes of inputs into a fluvial system to changes in output of the system was conceptually reviewed by Chorley *et al.* (1984). The concept developed for explaining landform recovery was defined in terms of recurrence interval, recovery time and event magnitude (Wolman and Gerson, 1978). These can be useful to explain balances between sediment stored in channels during storm events and sediment delivered from channels. Terrace deposits formed by the 1988 storm event have provided us with an opportunity to estimate magnitude and recovery time of channels. Trustrum *et al.* (1999) emphasized the need to consider the magnitude and frequency of storm events for elucidating sediment balances.

The study described here focuses on the influence of storm-related sediment storage on the overall sediment delivery ratio for catchments. In this paper, the sediment delivery ratio of concern is that calculated by dividing the volume of sediment transported from a tributary to the main stream by the volume of sediment generated at erosion sites in the tributary catchment. Because the volume of sediment that can be stored in each tributary catchment is in part controlled by that catchment's geomorphological characteristics (including catchment size and channel slope), the sediment delivery ratio is also influenced by such variables. This study examines this dependence by comparing geomorphological characteristics and sediment delivery ratios of two tributary catchments.

STUDY SITE

The Waipaoa River drains into Poverty Bay on the east coast of New Zealand's North Island (Figure 1(1) and 1(2)). The upper half of the 2205 km^2 catchment is dominated by hillslopes deeply incised by tributary channels. Highly crushed Cretaceous and Paleocene mudstones and argillites crop out in the headwaters (Mazengarb *et al.*, 1991), and the valley side slopes are susceptible to earthflow and deep amphitheatre-like gullies that can be up to 0·2 km^2 (DeRose *et al.*, 1998). The middle to low hills surrounding the Waipaoa floodplain are underlain by poorly consolidated sandstone and mudstones of Miocene and Pliocene age (Gage and Black, 1979) that are primarily susceptible to landsliding.

Large-scale clearance of the indigenous forest was initiated by European settlers in the 1830s and by the 1880s deforestation commenced in the headwaters in the lower catchment. By 1920 the later phase of deforestation was completed. Deforestation and conversion to pasture initiated a particularly intense phase of erosion and sedimentation, the effects of which are still shaping landscape morphology (Trustrum *et al.*, 1999). High intensity sub-tropical rainstorms have about a 10 year return period. The largest storm event to

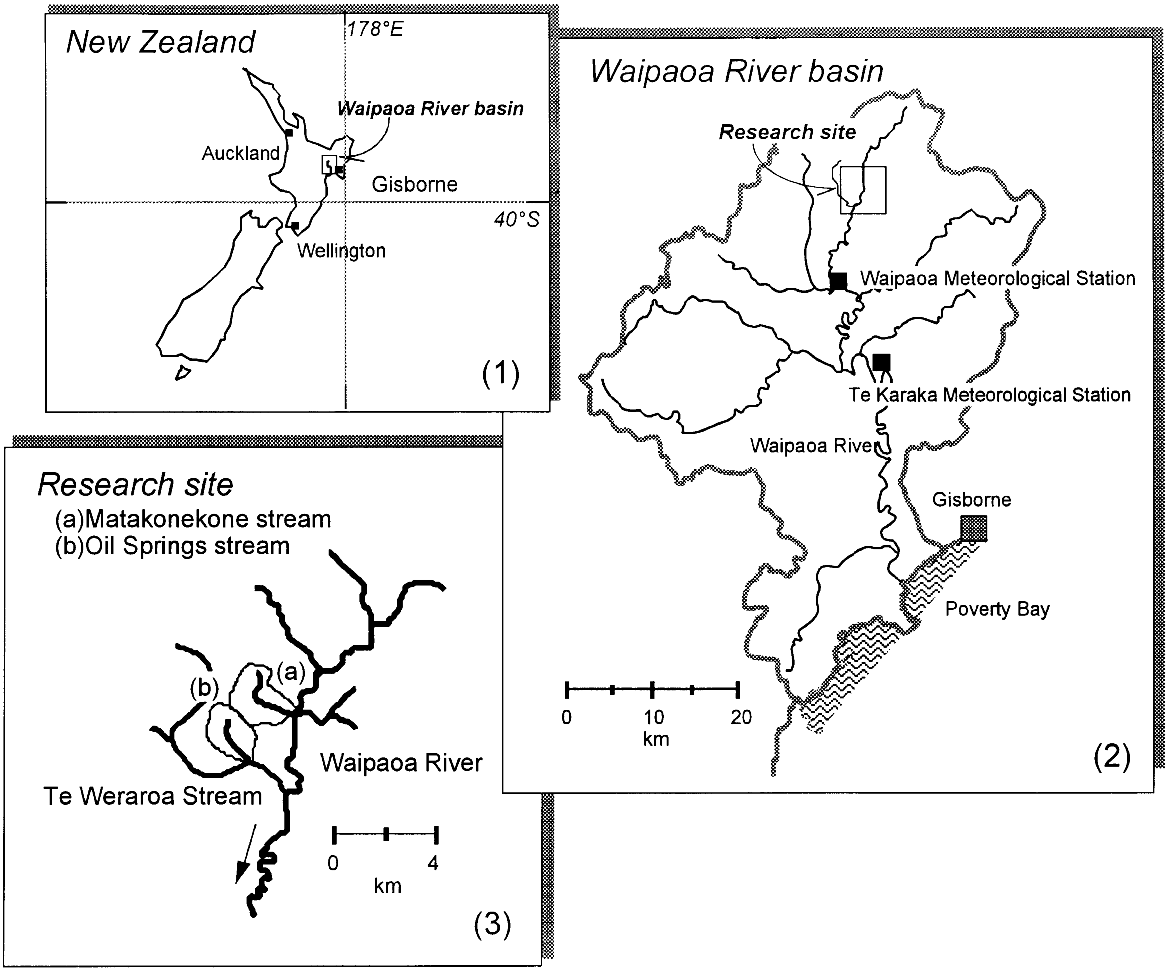

Figure 1. Location of Waipaoa River basin and two tributary catchments, Matakonekone stream and Oil Springs stream

occur in the historic period was Cyclone Bola in March 1988. There was a significant erosional response to this event and in the headwater region many existing gullies were expanded or new gullies initiated.

In this study, sediment delivery ratios were evaluated for the Oil Springs and Matakonekone tributaries to the upper Waipaoa River (Figure 1(3)). Oil Springs stream drains into the Te Weraroa River (itself a tributary to the Waipaoa River) whereas Matakonekone stream drains directly into the Waipaoa River. Since deforestation there has been significant aggradation of the channel systems. Over 10 m of aggradation has occurred in the Te Weraroa River since 1950 and anecdotal evidence suggests that there has been a similar amount of aggradation in both the Matakonekone and Oil Springs channels. Both catchments were under pastoral land use until the area was replanted in forest. Reforestation of Matakonekone catchment began in 1962 and of Oil Springs catchment in 1967.

In both tributary catchments, gullies are the dominant sediment source. Matakonekone catchment also contains landslides and an earthflow. Sediment is also generated from gullies and shallow landslides in Oil Springs catchment, but there are no earthflows. The spatial distribution of active gullies at 1960 and 1988 is shown for both tributaries in Figure 2. The 1988 map was drawn from aerial photographs taken 2 weeks after Cyclone Bola, hence many of the active gullies shown on the 1988 map represent a rejuvenated expansion of

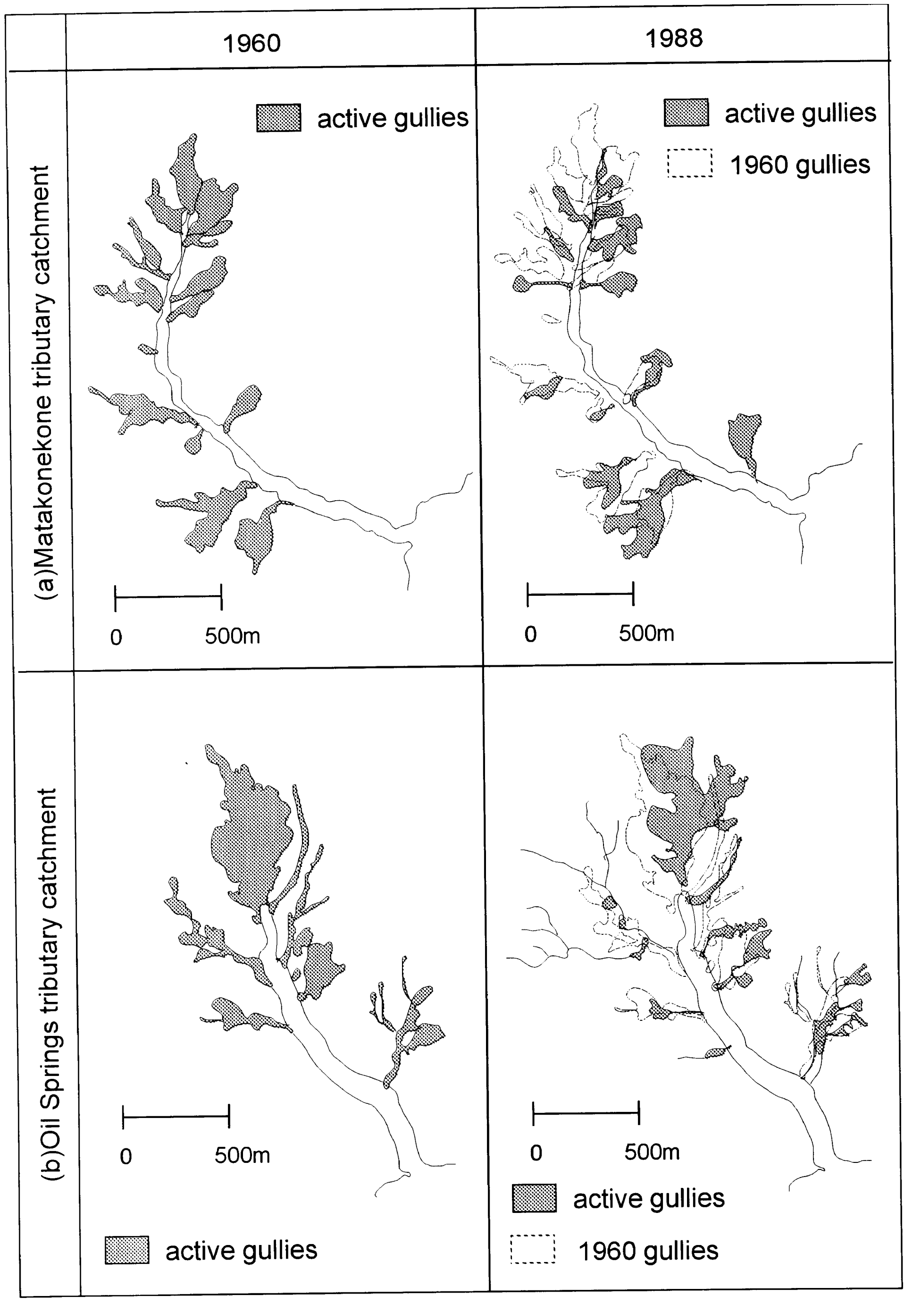

Figure 2. Changes in gully area of Matakonekone and Oil Springs tributary catchments between 1960 and 1988

gullies following Cyclone Bola. Immediately prior to Cyclone Bola in March 1988, the area of active gullies had reduced considerably (see position of 1960 gullies on the 1988 map).

The channel morphology and spatial and temporal distribution of terrace deposits was constructed from field surveys conducted in 1996 (Figure 3). The terraces date predominantly from 1960 and 1988. Some remnants of earlier deposits are delineated but they were of unknown age. The streams tend to be incised within the aggraded deposits and form a single thread along the river course and exhibit little tendency to meander or change course abruptly. Matakonekone catchment is 433·5 ha and the stream reach has an average

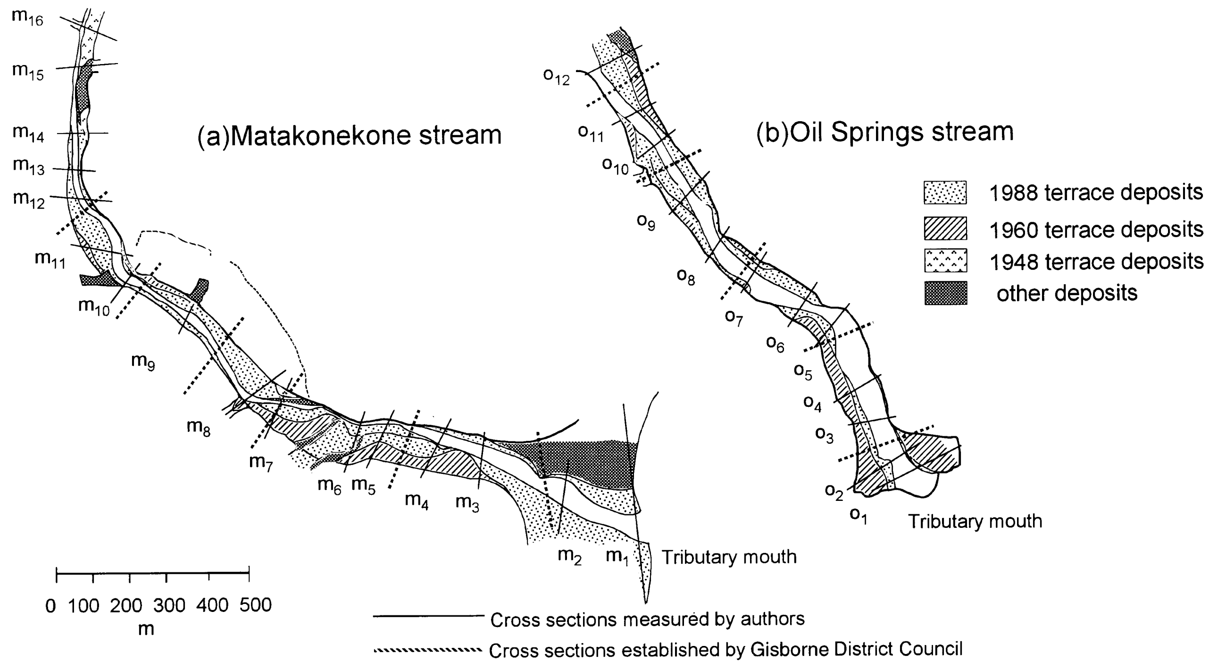

Figure 3. Channel planforms of Matakonekone and Oil Springs streams including the spatial distribution of 1960 and 1988 terrace deposits. Sixteen cross-sections (m_1 to m_{16}) were measured for Matakonekone and 12 cross-sections (o_1 to o_{12}) for Oil Springs

channel slope of 7·7 per cent and an average bankfull width of 29 m, while Oil Springs catchment is 305 ha with an average channel slope of 5·7 per cent and an average bankfull width of 45 m. Grain sizes of channel bed material along the Te Weraroa Stream are $2{\cdot}8 \pm 4{\cdot}3$ mm at the left bank and $3{\cdot}1 \pm 3{\cdot}2$ mm at the right bank (Banbury, 1996).

HISTORY OF STORM EVENTS

Sixteen large storms occurred in the Waipaoa catchment between 1914 and 1996 (Table I). Since 1947, rainfall has been gauged at Waipaoa Meteorological Station, located about 6 km downstream from the two tributary catchments. To obtain an index of likely magnitude of storm events prior to 1947, reference was made to the 74 year record of the Te Karaka rainfall gauge that was established in 1914 (located in the lower Waipaoa River, see Figure 1(2)). The portions of the longer-term Te Karaka records that corresponded to the years of record of the shorter-term upper Waipaoa site (1947–1998) were analysed and compared to make sure that the upper Waipaoa record was approximately collinear with the Te Karaka record. Then the corresponding long-term proportional relation was assigned to the upper Waipaoa site (Table I). Event rainfall is calculated as the sum of daily rainfalls occurring over the storm period, which is usually of 3 to 7 days' duration. Peak daily rainfall is the maximum daily rainfall over this period. The 1948 storm event produced 296 mm of rainfall in 3 days with a daily peak rainfall of 221 mm. In 1960, 319 mm of rain fell in 7 days with a daily peak rainfall of 141 mm. The 1988 Cyclone Bola event was remarkable for both event and daily rainfall totals, producing 431 mm of rainfall over 4 days and a peak daily rainfall of 174 mm.

Evidence of large storm-related sediment deposits remains in the terrace deposits of both Matakonekone and Oil Springs streams (Figure 3). Dating of these terrace deposits using tree age on the terrace surfaces indicates that a large amount of sediment storage has occurred in 1988 and 1960 and before 1948. The lowest terrace was identified as the remnant of the 1988 storm event and the highest terrace was attributed to the 1948 storm event. The middle terrace was also found to have formed in 1960 from tree ages. Thus the terraces

Table I. Event rainfall and peak daily rainfall since 1947 at the Waipaoa meteorological station. Values marked with an asterisk were calculated from a relationship established from Te Karaka meteorological station

Occurrence year	Event rainfall (mm)	Event duration (days)	Peak daily rainfall (mm)
1914	264*	–	–
1916	240*	–	–
1932	412*	–	–
1943	268*	–	–
1944	316*	–	–
1947	211	7	62·2
1948	296	3	221
1950	218	5	132·6
1954	287	5	104·4
1955	229	5	124·5
1960	319	7	141·2
1972	202	5	59
1975	216	5	79
1980	370	6	119·9
1987	215	5	67·5
1988	431	4	173·6

associated with the 1960 and 1988 storms provide consistent evidence of sediment storage in both tributaries (see Figure 5).

APPROACH

Sediment delivery ratio (*SDR*) for a tributary catchment is here defined as:

$$SDR = D/G \tag{1}$$

where D (m^3) is the volume of sediment delivered from the tributary catchment to the main stream, and G (m^3) is the volume of sediment generated from erosion site in the tributary catchment (Figure 4).

The volume of sediment delivered, D, can be calculated as the difference between sediment generation volume, G, and sediment storage volume, S (m^3), in the channel reach of the tributary catchment:

$$D = G - S \tag{2}$$

Equation 2 can then be substituted into Equation 1 and Equation 1 rearranged to solve for the delivery ratio:

$$SDR = (G - S)/G = 1 - S/G \tag{3}$$

The sediment generation volume, G, is usually equal to the total volume of sediment generated from all erosion sites in the catchment, and at the field sites considered here these sources would include shallow landslides, gullies and an earthflow. In the present study, however, the value of G includes only the volume of sediment generated from gullies, which were consistently the most important erosion sources. The contribution of sediment from the earthflow and from shallow landslides was small in comparison because the earthflow moves too slowly to generate much sediment and because the area occupied by shallow landslides is small in both of the study catchments.

In this paper we assume on the basis of field evidence that sediment deposition occurs primarily during major floods, and sediment storage volume, S, is defined as the volume of sediment in storage along the tributary valley and in the depositional fan at its mouth immediately after a flood. Because terrace deposits are remnants of the sediment deposited over a stream bed during a flood, if the age of the terrace can be determined, the value of S immediately after the flood can be calculated by assuming that the terrace height represents the depth of sediment deposited.

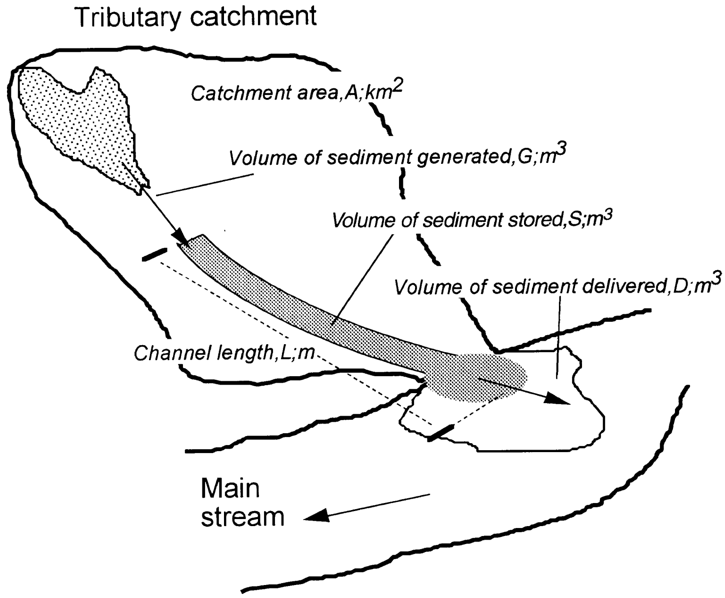

Figure 4. Idealized tributary catchment illustrating the variables used in equations. *G* is the volume of sediment generated from erosion site, *S* is the volume of sediment stored in the tributary channel and *D* is the volume of sediment delivered from the tributary catchment

VOLUME OF SEDIMENT GENERATED FROM EROSION SOURCES

Measurements

The volume of sediment generated from gullies in each tributary catchment during 1960–1988 was calculated from measurements made on aerial photographs dating from 27 January, 1960 (1:44 000) and 28 March 1988 (1:27 000). Each photo set post-dates a major flood, and thus represents catchment conditions following a major storm. Areas of shallow landslides and gullies were measured on each set of photographs. Errors in vertical and horizontal displacement associated with both sets of aerial photographs are calculated to be ±0·44 m (horizontal) and ±0·495 m (vertical) for the 1960 aerial photographs, and ±0·27 m (horizontal) and ±0·405 m (vertical) for the 1988 aerial photographs. Resolution of the 1960 aerial photographs is horizontally 57 per cent and vertically 22 per cent lower than the 1988 air photos.

The volume of sediment generated from each gully during each period was calculated from changes in cross-sectional areas measured at intervals along the gully axis. Cross-sections were measured using a

Table II. Total areas of gullies and shallow landslides, and depth of gullies in each catchment. Depths of gullies are represented as mean differences of elevation (m) at two arbitrary points on each aerial photograph. Standard deviations (SD) of each measurement are given

	Matakonekone catchment		Oil Springs catchment	
	1960	1988	1960	1988
Area (ha)				
Gullies	48·3	20·1	36·0	30·3
Shallow landslides	4·0	0·0	1·1	0·7
Total area	52·3	20·1	37·1	30·9
Depth (m)				
Mean differences of elevation ± SD	87·5 ± 5·0 (15 gullies)	18·9 ± 3·1 (6 gullies) 31·9 ± 2·7 (8 gullies)	87·5 ± 5·0 (10 gullies)	75·8 ± 2·4 (12 gullies)

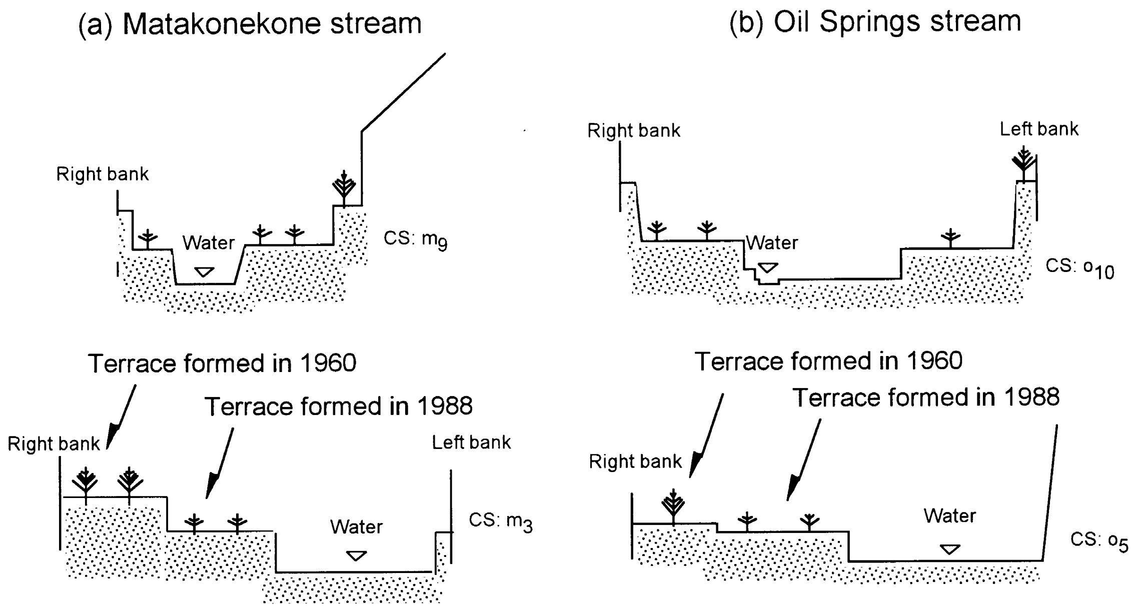

Figure 5. Examples of cross-sections measured for Matakonekone and Oil Springs streams. Each terrace surface supports vegetation of distinct characteristics and age

parallax bar. To assess the precision of the technique, standard deviations were calculated for repeated measurements of the difference in elevation between two arbitrary points on each of the aerial photographs. Standard deviations of elevations ranged between 2·4 and 5 m (Table II).

Calculations

Gully areas decreased between 1960 and 1988 aerial photographs (Table II). This decrease might be caused by reforestation dating from the 1960s. After 1960, shallow landslides account for less than 10 per cent of the eroded area in each catchment, suggesting that their sediment contribution is small relative to that of gullies for the period of this study. On this basis, sediment contributions from shallow landslides were not considered further and sediment generation volumes were calculated only for the gullies' contribution. The volume of sediment generated during the sequential photographic interval (1960–1988) and the corresponding average annual erosion rate are listed in Table III for each tributary catchment. The erosion rate for gullies in Oil Springs catchment was calculated at 105 500 m^3a^{-1} and in Matakonekone catchment at 47 000 m^3a^{-1} during 1960–1988.

SEDIMENT STORAGE VOLUMES IN THE TRIBUTARY STREAMS

Measurements

For the purposes of this study, sediment storage volume is defined as the volume of sediment that is contributed to the tributary channel by erosion during a major storm, but which is deposited along the channel rather than being exported to the main stream. The volume of sediment stored in the tributary channel can be calculated from measurements of cross-sections located along the tributary channel using methods similar to those described by Martin and Church (1995) and Madej and Ozaki (1996). As shown in Figure 3, in 1996 we surveyed 16 cross-section lines along Matakonekone stream and 12 along Oil Springs stream.

Table III. Comparison of sediment-related value of Matakonekone and Oil Springs tributary catchments

	Matakonekone catchment	Oil Springs catchment
Gully		
Event occurrence year	(1960–) 1988	(1960–) 1988
Sediment generation volume, G (m^3)	1 318 108	2 954 086
Erosion rate (m^3 a^{-1})	47 075	105 503
Tributary channel		
(storage)		
Event occurrence year	1988	1988
Sediment storage volume, S (m^3)	95 900	206 000
(scouring)		
Event occurrence year	1960–1996	1960–1996
Scouring rate (m^3 a^{-1})	12 543	8257
Main channel		
Sediment delivery volume, D (m^3)	1 222 208	2 748 086
Sediment delivery ratio, D/G	0·93	0·93

Valley bottoms along both tributary channels are characterized by the presence of terrace deposits above the current stream bed. Examples of cross-sections across these in-set terraces are represented in Figure 5. The cross-sectional morphology of each terrace is defined by a horizontal surface and vertical scarp. Therefore, each cross-section is regarded as a composition of rectangular terraces. To measure surface slope angle of sediment along cross-section lines and longitudinal profiles, a Suunto inclinometer mounted on 1 m ranging poles with an accuracy of $\pm 0{\cdot}5°$ (DeRose *et al.*, 1991) was used, and width of each terrace surface and distance between cross-section lines were measured to an accuracy of 100 m $\pm$ 3 mm using a Dist (Leica Co. Ltd) laser distance meter. Maximum error of a cross-sectional area was calculated at 6·24 m^2 for Matakonekone stream and at 9·63 m^2 for Oil Springs stream.

Each terrace surface supports vegetation of distinct characteristics and ages, suggesting that each surface was formed by a different flood. Because colonization by plants begins just after deposition of the surface, the successional stage or age of a plant community provides a good indicator of the age of the surface on which it grows. Terrace ages were first estimated by measuring the age of plants on each surface, generally by counting annual growth rings on *Pinus radiata*. Estimates were then refined by examining the rainfall record (see Table I) to determine the date of the major storm closely preceding establishment of the vegetation. Thus terraces dating between 1960 and 1996 were identified. The age of vegetation on each terrace surface provides evidence that floods which occurred between 1961 and 1996 did not overbank the 1960 terrace and floods which occurred after 1988 did not overbank the 1988 terrace. In both tributary catchments aggradation from smaller floods was deposited within the existing storm-related terrace.

Calculations

The cross-sectional area represented by each terrace was then evaluated using the idealized model illustrated in Figure 6: (a) a stream bed is first covered by new sediment during a large flood; (b) smaller flows during subsequent years gradually scour away some of the deposited sediment and incise a new channel; (c) another large flood occurs and once again buries the stream bed; and (d) new scour occurs. This model assumes that depositions occurs primarily during large floods. Deposition during smaller floods is expected to be relatively unimportant because little evidence of such deposition is visible in the field and temporal cross-sectional measurements also indicate constant scouring between large storms.

For example, the model is used as follows to calculate the cross-sectional area of sediment present in 1996 (X_{96}, m^2):

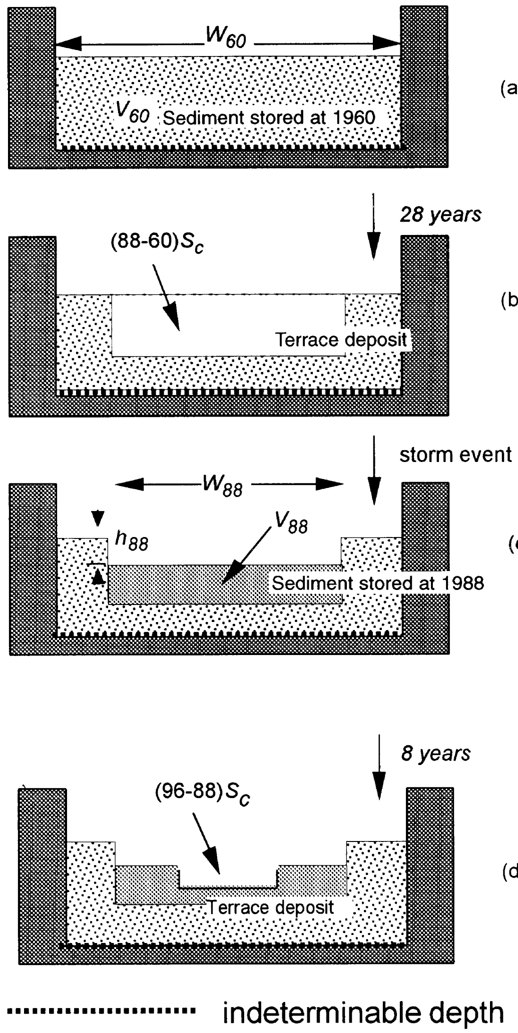

Figure 6. Idealized model of the change in a cross-section through time from 1960 to 1996, accompanied by storm events

$$X_{96} = (X_{88} + V_{88}) - (96 - 88)R_s \tag{4}$$

where R_s (m^2 a^{-1}) is the average annual sediment scouring rate, X_{88} (m^2) is the cross-sectional area of sediment present before the occurrence of Cyclone Bola in 1988, and V_{88} (m^2) is the cross-sectional area of sediment deposited by Cyclone Bola. In each case, cross-sectional areas also represent volumes per unit channel length.

The cross-sectional area of sediment present immediately before Cyclone Bola in 1988 (X_{88}) is calculated in the same way:

$$X_{88} = (X_{60} + V_{60}) - (88 - 60)R_s \tag{5}$$

where X_{60} is the cross-sectional area of sediment present before the large flood of 1960 and V_{60} is the cross-sectional area of sediment deposited by that flood.

Equation 5 can be rearranged to solve for R_s:

$$R_s = \{(X_{88} + V_{88}) - X_{96}\}/(96 - 88) \tag{6}$$

The value of $\{(X_{88} + V_{88}) - X_{96}\}$ can be calculated from field measurements of channel cross-sections, thus allowing solution for R_s at each cross-section.

Because the average annual scour rate (R_s) is expected to be determined primarily by catchment hydrology and gross channel morphology (e.g. channel slope and width), and because recovery of channel morphology follows a consistent pattern after disturbance, the time-averaged value of R_s is assumed to have remained approximately constant at any point along a channel over the period between 1960 and 1996. This is substantiated by Gisborne District Council cross-sections measured between 1976 and 1986 at Matakonekone stream, and between 1977 and 1986 at Oil Springs stream (dotted lines in Figure 3) which show that sediment storage volumes in both channels have degraded with a constant scouring rate (Figure 7).

However, downstream increases in average discharge and decreases in channel slope produce a consistent pattern of downstream variation in R_s (Figure 8). In Matakonekone catchment:

$$R_s = 26 \cdot 9e^{-0 \cdot 0021L} \qquad r^2 = 0 \cdot 91 \tag{7}$$

and in Oil Springs catchment:

$$R_s = 13 \cdot 8e^{-0 \cdot 0014L} \qquad r^2 = 0 \cdot 88 \tag{8}$$

where L (m) is the distance upstream along the stream course from each catchment mouth. Applying the F-test, we obtained $F = 13{\cdot}19$ (df = 2, 11) for Matakonekone stream and $F = 17{\cdot}38$ (df = 2, 8) for Oil Springs stream, so both equations were accepted at the 0·01 confidence limit.

The change in cross-sectional area between 1988 and 1996 can be described by subtracting Equation 5 from Equation 4:

$$X_{96} - X_{88} = \{(X_{88} + V_{88}) - (X_{60} + V_{60})\} + 20R_s \tag{9}$$

The values of $(X_{88} + V_{88})$ and $(X_{60} + V_{60})$ represent the cross-sectional area of sediment present after each large flood. The difference between two of these values (e.g. $(X_{88} + V_{88}) - (X_{60} + V_{60})$) is simply the cross-sectional area of scour below the 1960 flood-deposit surface and above the 1988 flood-deposit surface. For each sequential pair of surfaces, this area can be approximated as a rectangle (see Figure 5), and Equation 9 can be rephrased in terms of the dimensions of the rectangles:

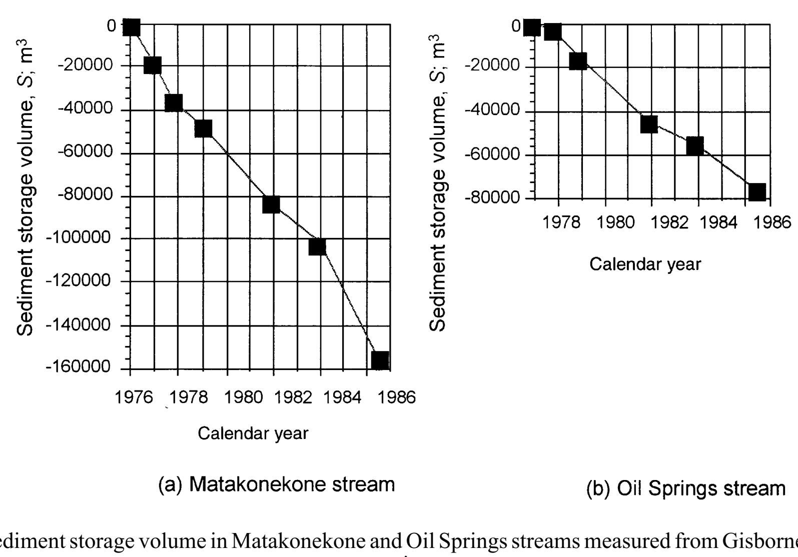

Figure 7. Changes in sediment storage volume in Matakonekone and Oil Springs streams measured from Gisborne District Council cross-sections

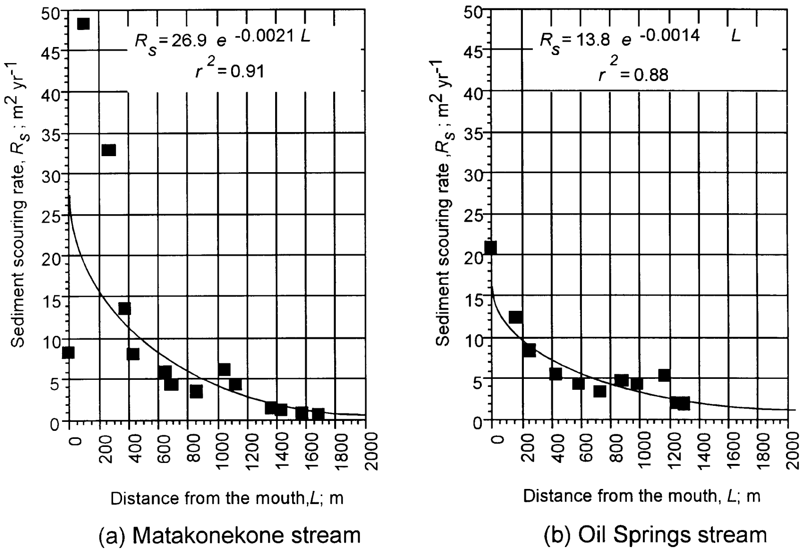

Figure 8. Changes in sediment scouring rate, R_s (m^2 a^{-1}) along the channel course

$$X_{96} - X_{88} = h_{88}w_{88} + 20R_s \tag{10}$$

where h_{88} is the vertical distance between the 1960 and 1988 flood-deposit surfaces and w_{88} is the width of the 1988 flood deposit.

Equation 4 can now be rearranged and Equation 10 substituted into the resulting equation to solve for V_{88} in terms of variables that can be easily measured in the field (h_{88} and w_{88}) or that are already known (R_s):

$$\begin{aligned} V_{88} &= X_{96} - X_{88} + (96 - 88)R_s \\ &= h_{88}w_{88} + 28R_s \end{aligned} \tag{11}$$

The variation of R_s along Matakonekone and Oil Springs streams is described by Equations 7 and 8, and these expressions can be substituted into Equation 11 to provide a description of the long-channel variation in depositional volumes for the 1988 and 1960 floods. For Matakonekone:

$$V_{88} = h_{88}w_{88} + 28(26 \cdot 9\mathrm{e}^{-0 \cdot 0021L}) \tag{12a}$$

and for Oil Springs:

$$V_{88} = h_{88}w_{88} + 28(13 \cdot 8\mathrm{e}^{-0 \cdot 0014L}) \tag{12b}$$

The volume of sediment deposited by the 1988 flood in each catchment is then calculated by these equations over the length of the corresponding stream. Assuming that the sediment volume can be represented by the frustum of a pyramid, the resulting values are the storage volumes (S_{88}) for 1988 flood, as follows:

$$S_{88} = \int_0^L V_{88}\ \mathrm{d}L$$

$$\cong V_{0-1} + V_{n-L} + \sum_{i=1}^{n}\left[\frac{(L_i - L_{i-1})}{3}(h_{88,i}w_{88,i} + h_{88,i-1}w_{88,i-1}) + \right. \tag{13}$$

$$\left.\sqrt{h_{88,i}w_{88,i} + h_{88,i-1}w_{88,i-1}}\right] + 28\int_0^L R_s\ \mathrm{d}L$$

where n is the number of cross-sections, $h_{88,i}$ and $w_{88,i}$ represent the height difference and deposit width for 1988 at the ith cross-section from the mouth. V_{0-1} is the volume between the confluence and the first cross-section and is calculated by assuming that the cross-sectional area at the confluence equals that at the first cross-section:

$$V_{0-1} = (h_{88,i} w_{88,i}) L_i \tag{14}$$

Similarly, V_{n-L} is the volume upstream of the last cross-section and is calculated as the volume of the frustum of a pyramid with a base equal to the cross-sectional area of the last cross-section:

$$V_{n-L} = (1/3)(h_{88,n} w_{88,n})(L - L_n) \tag{15}$$

Calculations for Matakonekone catchment indicate that $0{\cdot}96 \times 10^5$ m^3 of sediment was contributed to storage during Cyclone Bola with a maximum error of $0{\cdot}11 \times 10^5$ m^3. Oil Springs channel stored $2{\cdot}06 \times 10^5$ m^3 of sediment from Cyclone Bola with a maximum error of $0{\cdot}13 \times 10^5$ m^3.

ANNUAL VOLUME OF SEDIMENT SCOURED AND STREAM POWER

The average annual sediment yields due to scouring of flood deposits in each tributary can be calculated by integrating Equations 7 and 8 over the lengths of each channel undergoing erosion (L_u). The eroding channel length is measured from the upstream-most location of scour to the mouth of the tributary channel. The average sediment yields due to scouring in Matakonekone stream (Y_{sM}) and Oil Springs stream (Y_{sO}) are thus calculated for each channel from the upstream-most location of scour to the mouth of each fan:

$$Y_{sM} = \int_0^{L_u} R_s \, dL = \int_0^{L_u} 26 \cdot 9 \, e^{-0{\cdot}0021L} dL = \frac{-26 \cdot 9}{0 \cdot 0021}(e^{-0{\cdot}0021L_u} - 1) \tag{16a}$$

$$Y_{sO} = \int_0^{L_u} R_s \, dL = \int_0^{L_u} 13 \cdot 8 e^{-0{\cdot}0014L} dL = \frac{-13 \cdot 8}{0 \cdot 0014}(e^{-0{\cdot}0014L_u} - 1) \tag{16b}$$

The value of L_u measured for Matakonekone stream is 1845 m, so the average sediment yield due to scour is $1{\cdot}25 \times 10^4$ m^3 a^{-1}. A similar calculation for Oil Springs stream, which has a scoured channel length of 1312 m, indicates an average sediment yield due to scour of $0{\cdot}83 \times 10^4$ m^3 a^{-1}. Matakonekone stream thus appears to be more susceptible to scour than Oil Springs stream. The calculated scouring rates represent 27 per cent and 8 per cent of the average annual erosion rate between 1960 and 1988 in Matakonekone and Oil Springs catchments, respectively (see Table III).

The scouring rate is expected to be strongly influenced by the stream power (P_s) of a stream, which is calculated as the product of discharge (Q) and channel slope (I):

$$P_s = QI \tag{17}$$

The rational equation can be used to estimate discharge, allowing Equation 17 to be rewritten as:

$$P_s = (1/3{\cdot}6) f r_i A I \tag{18}$$

where f is the runoff coefficient, r_i is the rainfall intensity, A is the catchment area, and I is the average channel slope. The values of f and r_i are expected to be equal in Matakonekone and Oil Springs catchments because the catchments are contiguous. The ratio of average stream powers between the basins can thus be calculated from measurements of their catchment areas and average channel slopes:

$$\frac{P_{sM}}{P_{sO}} = \frac{\frac{1}{3{\cdot}6} f r_i 4335 \times 0{\cdot}135}{\frac{1}{3{\cdot}6} f r_i 3050 \times 0{\cdot}100} = 1 \cdot 9 \tag{19}$$

Table IV. Comparison of scouring rate of each tributary with the scouring rate calculated from stream bed change measured by Gisborne District Council

	Matakonekone stream	Oil Springs stream
Gross volume of sediment scoured by calculation from author's measurement		
(1988–1996)	100 344 (8 years)	66 056 (8 years)
Scouring rate	12 543	8 257
Gross volume of stream bed change by measurement conducted by Gisborne D.C.		
(1976–1986)	156 838 (10·7 years)	
(1977–1986)		76 503 (9 years)
Scouring rate	14 658	8 500

Average stream power in Matakonekone stream (P_{sM}) is thus expected to be approximately twice that in Oil Springs stream (P_{sO}) owing to the steeper channel slope (1·35 times greater than in Oil Springs) and larger area of Matakonekone catchment (1·42 times greater). The higher sediment yield due to scour in Matakonekone stream (1·51 times greater) is consistent with the higher stream power expected there.

CHANGES IN VOLUME OF SEDIMENT STORED IN TRIBUTARY CHANNELS

In both catchments, field evidence indicates that the only significant components of sediment storage located between the erosion sources and the main-stem channel are caused by major floods. Overall sediment delivery ratios thus depend on the factors that promote or inhibit sedimentation during floods. Matakonekone and Oil Springs streams respond to extreme storms by instantaneously aggrading at $(0{\cdot}96 \pm 0{\cdot}11) \times 10^5$ m^3 and $(2{\cdot}06 \pm 0{\cdot}13) \times 10^5$ m^3 respectively. Although large volumes of sediment are initially deposited at a flood event, subsequent smaller flows scour away much of these deposits.

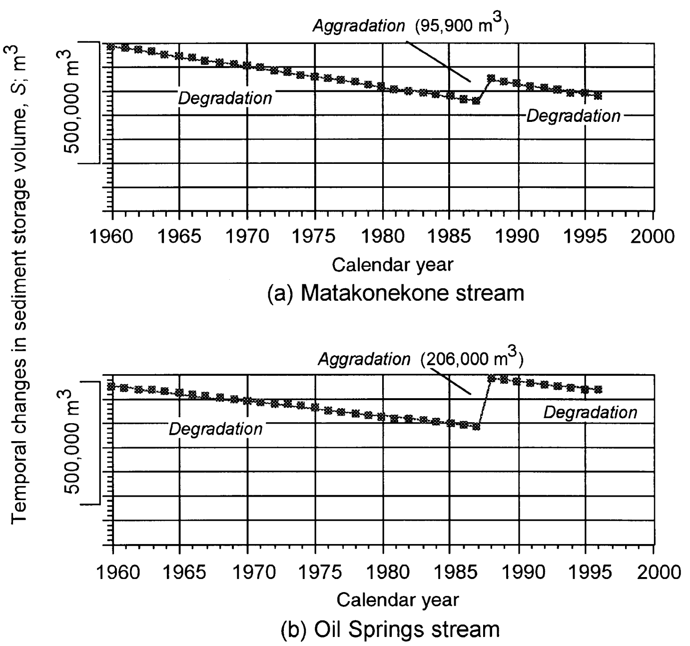

Figure 9. Predicted changes in sediment storage volume from 1960 for each stream. Vertical axis could not be represented by absolute values because the volume of gross sediment stored in stream channels is unknown (see also Figure 6)

The calculated average rate of sediment scouring from storage is $1{\cdot}25 \times 10^4$ m^3 a^{-1} for Matakonekone stream and $0{\cdot}83 \times 10^4$ m^3 a^{-1} for Oil Springs stream, as calculated for the period between 1988 and 1996. In the absence of another major storm, the volume of sediment in storage in both catchments can be expected to continue decreasing at the calculated average rates:

$$\mathrm{d}S_M/\mathrm{d}t = -Y_{sM} = -1 \cdot 25 \times 10^4 \text{ (Matakonekone stream)} \tag{20a}$$

$$\mathrm{d}S_O/\mathrm{d}t = -Y_{sO} = -0 \cdot 83 \times 10^4 \text{(Oil Springs stream)} \tag{20b}$$

where S_M (m^3) and S_O (m^3) are the volumes of sediment in storage and t is time (years). The calculated rates of scour can be compared to those calculated from cross-sections measured by the Gisborne District Council (Table IV). The gross volume of stream bed change of Matakonekone stream between 1976 and 1986 is averaged at $-1{\cdot}46 \times 10^4$ m^3 a^{-1}, and that of Oil Springs stream between 1977 and 1986 at $-0{\cdot}85 \times 10^4$ m^3 a^{-1}. This confirms that the sediment scouring rate would be approximately constant.

The volume of sediment in storage increased considerably in 1988, then there was a return to the long-term trend of gradual excavation of the temporarily stored sediment and consequent decrease in the volume of sediment stored for both tributaries. These can be represented as a series of volumetric changes in sediment stored (Figure 9). Chorley *et al.* (1984) have defined ‘relaxation time’ to describe the period over which such recovery occurs, and Wolman and Gerson (1978) use ‘recovery time’ in the same context. Many examples of geomorphic relaxation or recovery show an exponential decrease in recovery rate with time after a disturbance, and it is possible that dS/dt may also decrease exponentially after a flood. However, the assumption of a constant recovery rate used in this paper is supported by cross-sectional monitoring data. It is notable that the peak volumes of sediment storage in both Matakonekone and Oil Springs streams in 1988 have rejuvenated to those in 1960.

Both Chorley *et al.* (1984) and Wolman and Gerson (1978) describe disturbance events in terms of their recurrence intervals, and results from Matakonekone and Oil Springs streams suggest a mechanism by which event recurrence interval, rather than event magnitude, can strongly influence the magnitude of a geomorphic change. In this case, the magnitude of geomorphic change is indicated by the volume of sediment added to storage during a storm. If storage-producing storms have long enough recurrence intervals, then much of the stored sediment can be excavated by the time the next event is likely to occur, and a larger proportion of the storm-generated sediment can be stored.

SEDIMENT DELIVERY VOLUME AND SEDIMENT DELIVERY RATIO

The volume of sediment delivered to the main stream in 1988 can now be calculated by substituting the values of G and S calculated in preceding sections into Equation 2. This calculation indicates that $1{\cdot}22 \times 10^6$ m^3 of sediment was delivered by Matakonekone stream in the 1988 flood event. Oil Springs catchment contributed $2{\cdot}75 \times 10^6$ m^3 of sediment at the same time. These values have the same errors as those of sediment storage volume, being $\pm 0{\cdot}11 \times 10^5$ m^3 for Matakonekone stream and $\pm 0{\cdot}13 \times 10^5$ m^3 for Oil Springs stream respectively; however, these errors are small (<1 per cent) when compared to total sediment delivery volume. Results thus indicate that Oil Springs catchment has contributed more than twice the volume of sediment to the Waipaoa River that Matakonekone catchment has contributed. The sediment delivery ratio for the 1988 storm event in each catchment can also be calculated from the values of G and S calculated above. Substitution of these values into Equation 3 indicates a sediment delivery ratio of 0·93 for Matakonekone and Oil Springs catchments.

Sediment temporally stored in tributary channels has continued to be transported to the main stream since the 1988 storm event at the rate of $1{\cdot}25 \times 10^4$ m^3 a^{-1} for Matakonekone stream and $0{\cdot}83 \times 10^4$ m^3 a^{-1} for Oil Springs stream. Within the context of the relaxation times and related magnitudes of geomorphological changes, it is tempting to conclude that the relaxation time required to remove all sediment stored by the 1988 storm event is $7{\cdot}7 \pm 0{\cdot}8$ years for Matakonekone and $24{\cdot}8 \pm 1{\cdot}5$ years for Oil Springs stream.

Because we were unable to calculate precisely the errors associated with the method we employed to measure sediment generation volumes, the accuracy of sediment delivery volumes and sediment delivery ratios could not be confirmed. In this case it did not affect the outcomes of our result because firstly, the gross volume of sediment generated was significantly larger than the volume of sediment stored in the channel, and secondly, storm-related sediment delivery was strongly influenced by sediment generation. Hence the sediment delivery ratio could still be derived with high accuracy.

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